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TECHNICAL NOTES

Catastrophe characteristics of the condensation and pool boiling phenomena

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1. INTRODUCTION

CONDENSATION and boiling are well known as the important phase-change heat transfer processes which occur in numerous engineering applications. The condensation and pool boiling curves [1] reveal, as shown in Fig. 1, the relationship between the difference in temperature and heat flux when the saturated vapor is condensed on the subcooled surface and the saturated liquid is boiled on the super-heated wall, respectively. In liquid pool boiling, the mode of heat transfer is shifted from convection to nucleate boiling, then to transition boiling and to film boiling finally, with the increase from small values to very large wall superheat. The mode of condensation is changed from dropwise to film condensation, with the increase in the surface subcooling. During the condensation and pool boiling processes, some factors (such as the surface subcooling or wall superheat, heat flux, physical and chemical properties of the surface material) affect the change of the modes of the condensation and boiling phenomena. However, there remains a very significant task to extensively inspect the influences of the main factors on the whole processes of condensation and boiling.

Recently, Utaka *et al.* [2–4] proposed two types of the transition modes of dropwise condensation, i.e. the continuous and the jumping modes, and presented a criterion for determining the condensation transition mode. Stylianous and Rose [5] proposed two hypotheses, the coalescence-limited transition and the nucleation site saturation transition. Neither Utaka's criterion nor Rose's hypotheses could clearly interpret the physical mechanisms of the transitions both from filmwise to dropwise and from dropwise to pseudofilm condensation, and explicitly presented the main factors affecting the transitions. Kalinin *et al.* [6] have given a general review of the transition boiling heat transfer.

The catastrophe theory will be applied here to elucidate the complex phenomena of the transitions of the condensation and boiling pattern states.

2. CATASTROPHE THEORY

Catastrophe theory is a relatively new version of a more general mathematical theory of bifurcations. It was first introduced by Thom in the late 1960s, its basic thrust is to describe a discontinuous change in a system with the smooth change of one or several variables [7].

Among the seven elementary types of catastrophe theory, the cusp-type catastrophe has been the most widely used one [8]. The 3-dimensional potential function of cusp-type catastrophe is:

$$U = x^4 + ux^2 + vx \tag{1}$$

where u and v are the control variables, and x is the state variable. Hence, the equilibrium curved surface is composed of all of the critical points of the potential function, U, as following:

$$\text{grad}_x\, U = 4x^3 + 2ux + v = 0. \tag{2}$$

The points thus determined are called catastrophe points or singularity points. The projection of the catastrophe points in the control space constructs the bifurcation set to dominate the change of pattern states of the potential function, U. The bifurcation set is a semi-cubic parabola, i.e.

$$8u^3 + 27v^2 = 0. \tag{3}$$

Ito [9] applied the catastrophe theory to illustrate the breakup process of a liquid drop in a shear field. From the viewpoint of the cusp-type catastrophe, the catastrophe characteristics of the process were verified by the correlation of the experimental data. Lacy and his co-workers [10] investigated the structure of the thin wavy falling films with the methods of the deterministic chaos. By analyzing the experimental data on the time-varying film thickness, an attractor with two dimensional ring structure was constructed and the dynamical characteristics of the falling films were deduced also.

The catastrophe theory, chaos and bifurcation theory have been applied to the chemistry systems, chemical engineering and phase change processes. Moiola [11] presented some high-order Hopf bifurcation formulas to analyze the rich dynamic behavior of chemical systems under the failure of some hypotheses of the classical Hopf theorem. Kienle and Marouardt [12] investigated the steady-state multiplicity of the multicomponent distillation processes by means of the

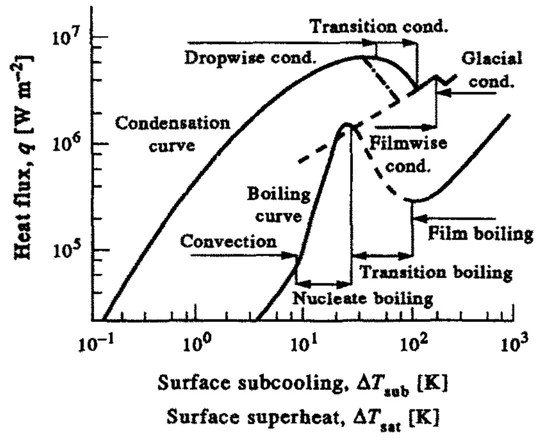

FIG. 1. Correspondence of boiling curve and condensation curve.

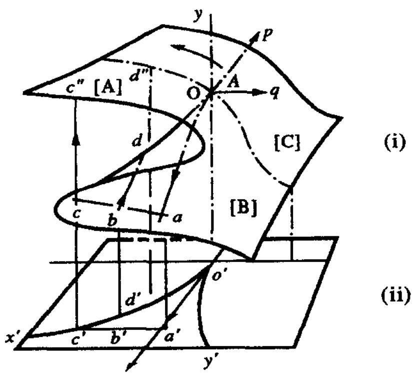

FIG. 2. The equilibrium curved surface and the bifurcation set of cusp-type catastrophe.

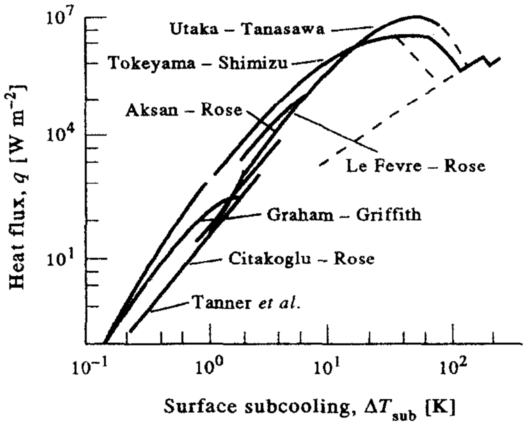

FIG. 3. Condensation curve [1].

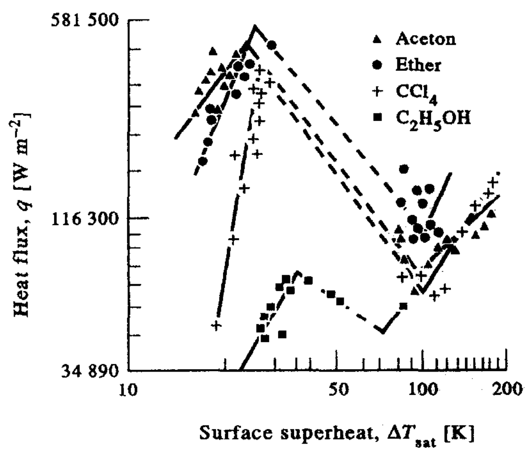

FIG. 4. Boiling curve [17].

bifurcation theory. Berezin [13] and Gaite [14] applied catastrophe theory to the phase transition problems.

3. CATASTROPHE CHARACTERISTICS OF CONDENSATION AND POOL BOILING TRANSITIONS

3.1. *Catastrophe characteristics of condensation transitions*

Dropwise condensation can only maintain surface subcooling up to a certain amount. At large surface subcoolings, so many active nuclei are present that a relatively thick continuous liquid film tries to form, thus a maximum heat flux occurs, and then the heat flux decreases and approaches the filmwise condensation curve with a continued increase in surface subcooling. Further increase in surface subcooling may result in a portion of the condensate actually freezing on the cold surface, and a pseudo-film condensation condition will exist. For steam, this is referred to as 'on-ice' condensation [15].

Subsequently, the transition from dropwise to film condensation results in a change of heat flux, and the factors affecting the condensation transition are not unique. We consider the transitions among the condensation pattern states as a discontinuous process and suppose as a cusp-type catastrophe, as shown in Fig. 2. The surface subcooling, ΔT_{sub} and the difference between the surface tension of the condensate and the surface free energy of the wall, $\Delta\sigma = (\sigma_L - \sigma_S)$ could be chosen as the control variables, heat flux, as the state variable. The control variables and the state variable determining the condensation pattern states are as follows:

$$x = f_1(q); \quad u = f_2(\Delta\sigma), \quad v = f_3(\Delta T).$$

In Fig. 2, parts A, B, and C represent the dropwise condensation region, the pseudo-film condensation region and the filmwise condensation region, respectively. The folding denotes the transition between dropwise and pseudo-film condensation. If the surface subcooling, ΔT_{sub} is constant, the condensate could wet the wall when $\Delta\sigma$ is less than 0, and therefore, the filmwise pattern state will occur. Otherwise, when $\Delta\sigma$ is greater than 0, the dropwise or pseudo-film pattern state takes place depending on the magnitude of the surface subcooling, ΔT_{sub}. It is obvious that the condensation curve is similar to one of the projecting curves [16]. Further experiments and theoretical analyses should be carried out to get the relationship among the supposed variables. At the same time, more attention would be focused on rectifying the two control variables, to identify with the equation (3). Some previous experimental results [1] are shown in Fig. 3.

3.2. *Catastrophe characteristics of the pool boiling pattern states*

Similar to the condensation, the transition from nucleate boiling to film boiling could also be regarded as a discontinuous one, and could be supposed as a cusp-type catastrophe. Figure 4 shows the boiling curves of some previous experiments [17]. The future task would be to also find the rational function between the control variables and the state variable.

4. CONCLUDING REMARKS

It is a new intention to interpret the discontinuous phenomena by the means of the catastrophe theory. The transitions of condensation and boiling pattern states could be regarded as a cusp-type catastrophe, and the processes of the condensation and boiling could be expected to get more comprehensive and rational insights than ever.

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Constant flux, turbulent convection data using infrared imaging

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INTRODUCTION

In recent years, the infrared (IR) imaging system has proven to be a powerful experimental tool for surface temperature mapping. This system has the advantage of being non-invasive, thus allowing measurements without interfering with the phenomenon under investigation. It also maps continuously the entire region of interest. The output can be displayed on a video screen, thus permitting real-time evaluation of the results [1]. It is believed that the IR imaging technique is as accurate as conventional thermocouples. Some recent applications of this technique in heat transfer include investigation of aerodynamic heating [2] and the detection of transition in a boundary layer flow [3].

This paper describes a recent study which obtained convection data using an IR imaging system in flow past a smooth surface. Since this study was carried out as an initial step in obtaining data for flow past roughened surfaces [4], friction factors were also determined. The project included the design and construction of a smooth test surface capable of providing uniform heat flux using electrically heated foils. Experimental data included surface temperature variation, pressure gradients, and mean velocity profiles. The data were analyzed and compared with numerical solutions.

EXPERIMENTAL FACILITIES

Experiments were conducted in an adjustable-height wind tunnel driven by a 74.6 kW fan. The discharge vent of the fan was 1.11 m wide and 0.93 m high. A transition section reduced the height to 0.38 m while the width remained the same at 1.11 m. The variable geometry section of the tunnel was 14.6 m long and 1.11 m wide. Its height could be varied from 5.1 to 38 cm, thus allowing operations at different hydraulic diameters. However, operation at a height less than 15 cm was found to be unsatisfactory due to mechanical vibration. The test section of the tunnel was 2.44 m long. A 3.35 m long diffuser region was located immediately downstream of the test section. The diffuser served to prevent end effects from being propagated upstream into the test section. The smooth test plate was 1.83 m long and 1.91 cm thick. It was constructed of birch which reduced heat losses due to conduction. To further minimize heat losses, the test plate was bonded with RTV silicone between two pieces of insulator IV3 Polyurethane, each 0.32 cm thick.

Uniform heating on the test surface was provided by 85 electrically heated metal strips which were glued to the top surface of the insulator with 3M two-part Epoxy. The metal strips, made of Type 302 Stainless Steel 2.0 cm wide, 0.0025 cm thick were spaced 0.1 cm apart. The heater strips on the test surface were divided into five sections of equal surface area. Each section consisted of 17 heater strips connected by copper bus bars attached to the sides of the test plate. Each heater section was connected to a 230 V, 6 A DC power supply having a maximum output of 700 W m^{-2}. To improve the thermal imaging process, a 32 cm width along the center line of the test plate was sprayed with black enamel paint to maximize thermal radiation.

Pressure taps along the top wall of the wind tunnel, including four taps in the test section, were used to measure wall pressure distributions. Velocity profiles were measured using a 32 cm pitot-static tube located about 35.5 cm upstream from the end of the test section. The vertical position of the probe was controlled by a Compumotor with increments varying from 0.5 to 1.3 cm and an accuracy of 0.025 cm.

The data acquisition system used in the present study consisted of an IBM XT computer, a Keithley Model 706